

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
13 January 2000 (13.01.2000)

PCT

(10) International Publication Number  
WO 00/001442 A3

(51) International Patent Classification<sup>7</sup>: A61N 1/378

(21) International Application Number: PCT/US99/15208

(22) International Filing Date: 6 July 1999 (06.07.1999)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
09/110,607 6 July 1998 (06.07.1998) US  
09/346,833 2 July 1999 (02.07.1999) US

(71) Applicant: ABIOMED, INC. [US/US]; 22 Cherry Hill Drive, Danvers, MA 01923 (US).

(72) Inventors: ZARINETCHI, Farhad; 9 Bradford Road, Chelmsford, MA 01863 (US). HART, Robert, M.; 81 Oakhill Drive, Arlington, MA 02174 (US). VERGA, Michael, G.; 11 Royce Road, Newton, MA 02459 (US). KEVILL, Stephen, J.; 38 Finn Road, Harvard, MA 01451 (US).

(74) Agent: VERGA, Michael, G.; Wolf, Greenfield & Sacks, P.C., 600 Atlantic Avenue, Boston, MA 02210 (US).

(81) Designated States (*national*): AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

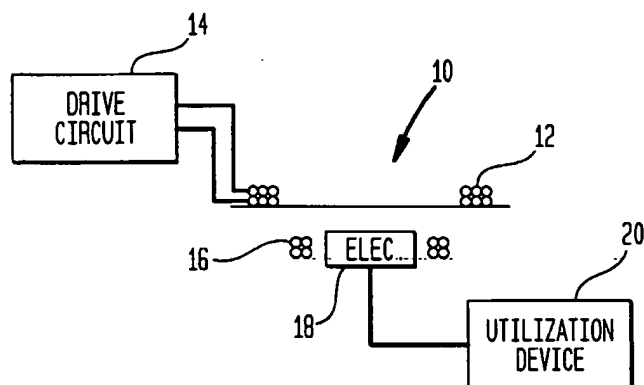
Published:

— with international search report

(88) Date of publication of the international search report:  
3 October 2002

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: TRANSCUTANEOUS ENERGY TRANSFER DEVICE WITH MAGNETIC FIELD PROTECTED COMPONENTS IN SECONDARY COIL



(57) Abstract: The invention provides a transcutaneous energy transfer device having an external primary coil and an implanted secondary coil inductively coupled to the primary coil, electronic components subcutaneously mounted within the secondary coil and a mechanism which reduces inductive heating of such components by the magnetic field of the secondary coil. For one embodiment of the invention, the mechanism for reducing inductive heating includes a cage formed of a high magnetic permeability material in which the electronic components are mounted, which cage guides the flux around the components to prevent heating thereof. For an alternative embodiment of

the invention, a secondary coil has an outer winding and either a counter-wound inner winding or an inner winding in the magnetic field of the outer winding. For either arrangement of the inner coil, the inner coil generates a magnetic field substantially canceling the magnetic field of the outer coil in the area in which the electronic components are mounted.

WO 00/001442 A3

## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 99/15208

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 A61N1/378

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61N H01F A61F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	DE 27 20 011 A (PACESETTER SYST) 16 November 1978 (1978-11-16) page 11, line 18 -page 12, line 10  ---	1-6,8, 15,16,23 7,13,14, 17-22,24
A	US 3 942 535 A (SCHULMAN JOSEPH H) 9 March 1976 (1976-03-09)  column 12, line 55 -column 13, line 9  --- -/--	1-6,9, 13-15, 20,23,25



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

## \* Special categories of cited documents:

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*&\* document member of the same patent family

Date of the actual completion of the international search

2 November 1999

Date of mailing of the international search report

11/11/1999

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Grossmann, C.

## INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US 99/15208

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>HIDETOSHI MATSUKI ET AL: "ENERGY TRANSFERRING SYSTEM REDUCING TEMPERATURE RISE FOR IMPLANTABLE POWER CONSUMING DEVICES" PROCEEDINGS OF THE 18TH ANNUAL CONFERENCE OF THE IEEE ENGINEERING I MEDICINE AND BIOLOGY SOCIETY, AMSTERDAM, OCT. 31 - NOV. 3, 1996, vol. 1, 31 October 1996 (1996-10-31), page 185/186 XP000787635 BOOM;H ET AL (EDS ) ISBN: 0-7803-3812-X</p>	1,13,15, 20,23,25

**INTERNATIONAL SEARCH REPORT**  
Information on patent family members

International Application No  
**PCT/US 99/15208**

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 2720011 A	16-11-1978	NONE	
US 3942535 A	09-03-1976	CA 1020233 A	01-11-1977
		DE 2446039 A	03-04-1975
		FR 2245334 A	25-04-1975
		GB 1492990 A	23-11-1977
		JP 50060085 A	23-05-1975
		NL 7412716 A	02-04-1975

**PCT**WORLD INTELLECTUAL PROPERTY ORGANIZATION  
International Bureau

## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : <b>A61N 1/00</b>	<b>A2</b>	(11) International Publication Number: <b>WO 00/01442</b> (43) International Publication Date: 13 January 2000 (13.01.00)
<p>(21) International Application Number: PCT/US99/15208</p> <p>(22) International Filing Date: 6 July 1999 (06.07.99)</p> <p>(30) Priority Data: 09/110,607 6 July 1998 (06.07.98) US 09/346,833 2 July 1999 (02.07.99) US</p> <p>(71) Applicant: ABIOMED, INC. [US/US]; 33 Cherry Hill Drive, Danvers, MA 01923 (US).</p> <p>(72) Inventors: ZARINETCHI, Farhad; 9 Bradford Road, Chelmsford, MA 01863 (US). HART, Robert, M.; 81 Oakhill Drive, Arlington, MA 02174 (US).</p> <p>(74) Agent: VERGA, Michael, G.; Wolf, Greenfield &amp; Sacks, P.C., 600 Atlantic Avenue, Boston, MA 02210 (US).</p>		<p>(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).</p> <p><b>Published</b> <i>Without international search report and to be republished upon receipt of that report.</i></p>
<p>(54) Title: <b>TRANSCUTANEOUS ENERGY TRANSFER DEVICE WITH MAGNETIC FIELD PROTECTED COMPONENTS IN SECONDARY COIL</b></p> <div data-bbox="487 1197 958 1512"></div> <p>(57) Abstract</p> <p>The invention provides a transcutaneous energy transfer device having an external primary coil and an implanted secondary coil inductively coupled to the primary coil, electronic components subcutaneously mounted within the secondary coil and a mechanism which reduces inductive heating of such components by the magnetic field of the secondary coil. For one embodiment of the invention, the mechanism for reducing inductive heating includes a cage formed of a high magnetic permeability material in which the electronic components are mounted, which cage guides the flux around the components to prevent heating thereof. For an alternative embodiment of the invention, a secondary coil has an outer winding and either a counter-wound inner winding or an inner winding in the magnetic field of the outer winding. For either arrangement of the inner coil, the inner coil generates a magnetic field substantially canceling the magnetic field of the outer coil in the area in which the electronic components are mounted.</p>		

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon	KR	Republic of Korea	PL	Poland		
CN	China	KZ	Kazakhstan	PT	Portugal		
CU	Cuba	LC	Saint Lucia	RO	Romania		
CZ	Czech Republic	LI	Liechtenstein	RU	Russian Federation		
DE	Germany	LK	Sri Lanka	SD	Sudan		
DK	Denmark	LR	Liberia	SE	Sweden		
EE	Estonia			SG	Singapore		

**TRANSCUTANEOUS ENERGY TRANSFER DEVICE**  
**WITH MAGNETIC FIELD PROTECTED COMPONENTS**  
**IN SECONDARY COIL**

**Related Application**

This application is a continuation-in-part of U.S. Patent Application 09/110,607 filed July 6, 1998 entitled "TET WITH MAGNETIC FIELD PROTECTED COMPONENTS IN SECONDARY COIL," and naming as inventors Fred Zarinetchi and Robert M. Hart, now currently pending.

The following commonly-owned application is related to the present application and its disclosure is incorporated by reference in the present application:

U.S. Patent Application entitled "MAGNETIC SHIELD FOR PRIMARY COIL OF TRANSCUTANEOUS ENERGY TRANSFER DEVICE", Serial No. 09/110,608, filed July 6, 1998, naming as inventors Fred Zarinetchi and Steven J. Keville, and now pending.

**Field of the Invention**

This invention relates to transcutaneous energy transfer (TET) devices and, more particularly, to such a device which includes a mechanism for protecting components mounted within a secondary coil from magnetic field induced heating.

**Background of the Invention**

Many medical devices are now designed to be implantable including pacemakers, defibrillators, circulatory assist devices, cardiac replacement devices such as artificial hearts, cochlear implants, neuromuscular simulators, biosensors, and the like. Since almost all of the active devices (i.e., those that perform work) and many of the passive devices (i.e., those that do not perform work) require a source of power, inductively coupled transcutaneous energy transfer (TET) and information transmission systems for such devices are coming into increasing use. These systems consist of an external primary coil and an implanted secondary coil separated by an intervening layer of tissue.

One problem encountered in such TET systems is that the best place to locate control circuitry for converting, amplifying and otherwise processing the signal received at the secondary coil before sending the signal on to the utilization equipment is within the

secondary coil itself. However, there is also a significant magnetic field in the secondary coil resulting from the current induced therein, which field can induce heating of the components, particularly metallic components. As a minimum, such heating can influence the performance of various components, and in particular interfere with the desired uniform power applied to the equipment. In a worst case, the heating can be severe enough to cause damage or  
5 destruction to the components which can only be repaired or replaced through an invasive surgical procedure. Such heating can also cause injury or discomfort to the patient in which the components have been implanted.

Heretofore, in order to avoid such heating, it has either been necessary to be sure that  
10 the signal induced in the secondary coil is not sufficient to generate a magnetic field which would cause potentially damaging heating of the components or to mount the components at a less convenient location. The former is undesirable because it is generally not possible to eliminate significant heating of the components while still operating the device at required energy levels, and the later solution is not desirable since the output signal from the secondary  
15 coil can reach 500 volts and above at an operating frequency that can be in excess of 100 kHz. It is preferable that such high voltage signal not pass extensively through the body and it is difficult to provide good hermetically sealed connectors for signals at these voltages. It is therefore preferable that an auxiliary signal processing module, which may reduce the voltage to a value in the approximately 20 volt range, be included as close to the secondary coil as  
20 possible, a position inside the secondary coil being ideal for this purpose.

A need therefore exists for an improved technique for use with TET devices so as to enable at least selected electronic components to be mounted within the secondary coil with minimal heating of such devices.

### Summary of the Invention

In accordance with the above, this invention provides a transcutaneous energy transfer device which includes an external primary coil to which energy to be transferred is applied, an implanted secondary coil inductively coupled to the primary coil, each of the coils generating a magnetic field, and electronic components subcutaneously mounted within the secondary  
30 coil, with a mechanism being provided which reduces inductive heating of such components by the magnetic field of the secondary coil. For one embodiment of the invention, the mechanism for reducing inductive heating includes a cage formed of a high magnetic



permeability material in which the electronic components are mounted. The material of such cage is preferably a ferromagnetic material such as a ferrite and is preferably sufficiently thick so that magnetic field values in the material are well below saturation and so that significant heat dissipation in the material does not occur. The material of the cage should however be as thin as possible while satisfying the above criteria. The cage may be thicker in areas of the cage experiencing high flux density and thinner in other areas. The cage may also be formed of a layer of ferromagnetic material laminated with at least one layer of a low magnetic conductivity material to enhance flux guidance.

Alternatively, the mechanism may include winding the secondary coil with a first number  $N_1$  of outer windings and a second number  $N_2$  of counter-wound inner windings,  $N_1$  being larger than  $N_2$ .  $N_1$ ,  $N_2$  and the diameters of both the outer and inner windings are selected such that the magnetic field caused by the coils in the region of the components is reduced sufficiently to prevent significant component heating. For a preferred embodiment,  $N_1$ ,  $N_2$ , and the diameters of the windings are selected so that the magnetic fields caused by the windings substantially cancel in the region of the components. For an illustrative embodiment,  $N_1$  is approximately 19,  $N_2$  is approximately 7, and the diameter of the outer winding is approximately 2.5 inches, and the diameter of inner winding is approximately 1.5 inches. Alternatively, the inner windings may be in the magnetic field of the outer winding, but not electrically connected thereto.

In another aspect of the invention, a transcutaneous energy transfer device is disclosed. The TET includes an external primary coil; an implantable secondary coil coupled to the primary coil; a cage formed of a high magnetic permeability material located within the secondary coil to reduce inductive heating of electronic components mounted therein caused by a magnetic field of the primary and secondary coils, wherein the cage has walls of varying thickness such that a lowest total mass is achieved without exceeding the saturation density of the cage material. In one embodiment, the thickness of the cage walls is a minimum thickness that results in magnetic flux density through the cage walls is approximately equal to the saturation density.

In another aspect of the invention, another transcutaneous energy transfer device is disclosed. This TET includes an external primary coil; an implantable secondary coil coupled to the primary coil; and a cage formed of a high magnetic permeability material located within the secondary coil to reduce inductive heating of electronic components mounted therein

caused by a magnetic field of the primary and secondary coils, wherein the cage has a geometry configured to maximize permeability in flux pathway between the primary and secondary coils. In one embodiment, the cage has flanges that extend the high permeability shield material within the flux pathway.

5 In another embodiment of this aspect of the invention, the cage includes a cylindrical base; a lid shaped in the form of a disk; and the flanges integral with the base. The flanges extend a high magnetic permeable region from base into the magnetic flux pathway. Preferably, the flange is in-line with a shortest flux pathway between the primary and secondary coils, such as extending from base immediately adjacent to the secondary coil to  
10 guide the magnetic flux lines back toward the primary coil.

In another aspect of the invention, a transcutaneous energy transfer device is disclosed. This TET includes an external primary coil; an implantable secondary coil coupled to the primary coil; and a cage formed of a high magnetic permeability material within the secondary coil to house electronic components. The cage includes a base; and a self-aligning  
15 lid.

In one embodiment of this aspect of the invention, the base is cylindrical and the lid is shaped in the form of a disk. In another embodiment, the base includes vertical walls. The lid includes an annular recessed shelf circumferentially formed around a mating surface of the lid configured to receive the vertical wall of the base.

20 In a further aspect of the invention, a transcutaneous energy transfer device is disclosed. The device includes an external primary coil; an implantable housing formed of a substantially low thermal conductivity medium; a secondary coil, mounted within the implantable housing, coupled to the primary coil; a cage formed of a high magnetic permeability material within the secondary coil to house electronic components; and a heat  
25 distribution layer thermally coupled to the cage and to an internal surface of the housing. The heat distribution layer may be comprised of multiple alternating layers of high and low heat conductivity materials.

In a further aspect of the invention, a transcutaneous energy transfer system is disclosed. The TET includes a primary coil and an implantable secondary coil having an  
30 outer first winding having a first number of turns and a first diameter and an inner second winding having a second number of turns and a second diameter. A method for determining the second number of turns, includes the steps of: a) winding the first winding with a

predetermined number of turns; b) inserting a magnetic field monitoring device in a central region of the secondary coil; c) applying a dc current through the first winding while monitoring a magnetic field in the central region; d) winding the second winding in a direction a direction of the first winding using a wire extension from the first winding; e) monitoring, as  
5 the second winding is wound in the step d), a strength of a magnetic field in the central region; and f) stopping the winding of the second winding when the magnetic field strength reaches approximately zero.

Further features and advantages of the present invention as well as the structure and operation of various embodiments of the present invention are described in detail below with  
10 reference to the accompanying drawings. In the drawings, like reference numerals indicate like or functionally similar elements. Additionally, the left-most one or two digits of a reference numeral identifies the drawing in which the reference numeral first appears.

#### **Brief Description of the Drawings**

15 This invention is pointed out with particularity in the appended claims. The above and further advantages of this invention may be better understood by referring to the following description when taken in conjunction with the accompanying drawings, in which:

Figure 1 is a schematic semi-block diagram of an exemplary TET system.

Figure 2 is a cutaway sectional view of the secondary coil and electronics for a system  
20 of the type shown in Figure 1 in accordance with a first embodiment of the invention.

Figures 3A and 3B are a side-sectional view and a top plane view respectively of a secondary coil and electronics in accordance with a second embodiment of the invention.

Figure 3C is a top view for an alternative second embodiment.

Figures 4A, 4B and 4C are side-sectional views of the secondary coil and electronics  
25 illustrating the magnetic field lines at the secondary for the embodiment shown in Figure 1, Figure 2, and Figures 3A -3C respectively.

Figure 5 is a cross-sectional view of an alternative embodiment of a cage of the present invention having flanges or extensions extending therefrom.

Figure 6 is a simplified cross-sectional view of a cage in accordance with one  
30 embodiment of the present invention.

Figure 7 is a cross-sectional view of an implantable device housing a secondary coil in accordance with an alternative embodiment of the present invention.

### Detailed Description

Referring to Figure 1, an exemplary TET system 10 is shown which includes a primary coil 12 connected to receive an alternating drive signal from an appropriate drive circuit 14 and a transcutaneously mounted secondary coil 16 having signal processing electronics 18 mounted therein. The signal from electronics 18 is applied to operate a utilization device 20 which may for example be a blood pump, artificial heart, defibrillator, or other implanted device requiring power or other signals applied thereto. As illustrated in Figure 4A, the magnetic field lines generated by the secondary coil 16 pass through the electronics 18 for the embodiment shown in Figure 1, resulting in heating of the electronics and, in particular, metal portions thereof. This can cause undesired variations in the outputs from this device or, worst case, in component failure. In accordance with certain aspects of the present invention, Figures 2 and 3A-3C illustrate two techniques for reducing inductive heating of such electronic components 18 by the magnetic field generated by the primary and secondary coils.

Referring to Figure 2, the electronics 18 are fully enclosed within a cage 22 formed of a high magnetic permeability material, the material for cage 22 preferably having a magnetic permeability in the range of approximately 2000-5000. Cage 22 is formed of a base 22A and a lid 22B which are fitted and held together in a manner known in the art which minimizes interruption of magnetic field lines passing through the cage. For a preferred embodiment, the material utilized for the cage is MnZn ferrite (Phillips 3F3), although other high magnetic permeability materials now or later developed may be used. The material is preferably one formulated for high frequency application with low power loss. Since it is desirable that cage 22 be as light (have minimal mass) as possible, the wall thickness (t) of the cage should be no thicker than is required to protect electronics 18 therein, preferably while minimizing heat loss. In particular, the thickness should be the minimum thickness for the material which provides magnetic field values in the material which are well below saturation, saturation preventing the flux from being guided effectively, and below the level that would lead to significant (for example, greater than 100mw) heat dissipation in the material under operating conditions. Saturation in the cage is a function of magnetic field strength, while heat generation is a function of both magnetic field strength and frequency. For a ferrite cage material, the field strengths and frequencies at which these effects occur can be tabulated. With a give set of operating conditions, field strength or flux density increases with

decreasing wall thickness. The magnetic field strength B may be determined by measurement at the top surface of the cage 22, and the total flux  $\Phi_t$  may be determined as the integral of B over the surface. This flux is guided through the side walls of the cage, density being highest in these side walls. The magnetic flux in the walls may then be calculated as the total flux divided by the cross sectional area of the wall:

$$B_{\max} = \frac{\Phi_t}{(\pi D t)} \quad \text{Eq. (1)}$$

A thickness t may be chosen so that  $B_{\max}$  is below the saturation level. In an alternative embodiment, the thickness t is also chosen so that the total heat dissipation at the operating frequency is less than 100mw. In another embodiment, the thickness t is also chosen so that the total heat dissipation at the operating frequency is between 50 and 100mw. In a still further embodiment, the thickness t is also chosen so that the total heat dissipation at the operating frequency is less than 150mw. In a another embodiment, the thickness t is also chosen so that the total heat dissipation at the operating frequency is between 70-90mw.

For an exemplary embodiment using the material previously indicated, wall thickness (t) is approximately 0.06 inches, and the diameter (D) of the cage for this embodiment is approximately 1.9 inches. However, these dimensions may vary significantly with application, for example the size of secondary coil 16, the electric energy applied thereto and the like. Further, the thickness of the cage need not necessarily be sufficient to divert all magnetic flux lines from the electronic 18 so long as it is effective to divert sufficient magnetic flux lines so as to prevent any significant heating of the electronic components. Figure 4B illustrates the magnetic field for secondary coil 16 when a cage 22 of the type shown in Figure 2 is employed. From Figure 4B, it can be seen that the magnetic field is concentrated in the high permeability material of the cage so that the field at the electronic components 18 is reduced to nearly zero, with the magnetic field concentration being higher in the sidewalls of the cage than in the top and bottom walls. Thus, overall cage thickness and weight may in some instances be reduced by making the sidewalls thicker to accommodate the flux therein, with the top and bottom walls of the cage being thinner.

In one preferred embodiment, the optimal thickness of the cage wall has the lightest weight (lowest mass) without causing excessive heat dissipation. To have the lightest cage

22, the cage wall thickness is reduced, resulting in an increase in the magnetic flux density,  $B$ . To satisfy operation without excessive heat dissipation,  $B$  must be kept below the saturation density,  $B_{\max}$ , for the selected cage material. Should  $B_{\max}$  be exceeded, the heat dissipation of the material increases dramatically. The combination of these two requirements, then, results in the desired requirement that  $B_0 = B_{\max}$ , where  $B_0$  is the flux density at the highest possible magnetic field strength for the device.

$B_0$  at any given point along the cage can be manipulated by varying the cage wall thickness. The design consideration is to reduce the cross sectional area of the cage so that  $B_0$  is less than or equal  $B_{\max}$  along a substantial portion of the cage wall. An example of an algorithm for this process for a cylindrically symmetric cage includes first assuming a uniform thickness for the cage wall. Then, the total flux for highest power transfer within the cage walls, i.e.  $\phi_0$  using the relationship  $B_0 = \phi_0 / Lt$ , where  $L$  is the perimeter of the cage 22 at the point of interest and  $t$  is the cage thickness wall. Given that  $L$  is determined by other design considerations,  $t$  can be adjusted so that  $B_0 = B_{\max}$ .

While for certain embodiments, the material of cage 22 is of a ferrite material, other high permeability materials might also be utilized such as, for example, laminated iron materials. For ease of fabrication, it may also be desirable to form the cage as three or more distinct segments, for example a top and bottom disk with a cylinder for the sidewalls, the disks and sidewalls being held together by a suitable epoxy, solder or other suitable means known in the art. This form of fabrication may be particularly desirable where the sidewalls are of a different thickness than the top and bottom walls. Preferably, the break in material continuity is minimized to avoid a significant reduction in the efficiency at which the magnetic field through the cage. Finally, forming the cage of alternate layers of ferrite material with high thermal and magnetic conductivity and epoxy or other similar material with low thermal and magnetic conductivity, results in a cage which is more anisotropic for magnetic flux flow, and thus provides potentially better flux guidance. In particular, such construction provides a lower reluctance path for the magnetic flux and magnetic fields through the ferrite layers than in a direction perpendicular thereto.

Figures 3A and 3B illustrate an alternative embodiment of the invention wherein reduced magnetic field at electronic components 18 is achieved by dividing the secondary coil into an outer coil 16A and an inner coil 16B which is counter-wound with the coil 16A so as to provide an opposing field. In this embodiment, the two sets of coils are connected so that

the same current flows in each. The relative diameters of the two coils,  $D_1$  and  $D_2$  and the number of turns for the coils,  $N_1$  and  $N_2$ , are adjusted so that their separate contributions to the total magnetic field at the location of components 18 significantly cancel each other. In achieving this objective, the field generated in the central region by a flat outer coil 16A is given by:

$$B_1 = \frac{\mu N_1 i}{D_1} \quad \text{Eq. (2)}$$

while the field generated by the inner coil 16B in the central region of the coil is given by:

$$B_2 = \frac{\mu N_2 i}{D_2} \quad \text{Eq. (3)}$$

When the strengths of these two fields are selected to be equal, the ratio between the outer and inner windings becomes:

$$\frac{N_1}{N_2} = \frac{D_1}{D_2} \quad \text{Eq. (4)}$$

Using these criteria with an illustrative embodiment where  $D_1 = 2.5$  inches,  $D_2 = 1.5$  inches and  $N_1 = 19$ , a value for  $N_2 = 11.4$  would be obtained. However, for this implementation, because the inner coil was slightly elongated along the field direction, a preferred value for  $N_2$  was found to be 7. Therefore, while the four values (the N and D values) can be calculated to achieve the desired magnetic field cancellation for a given application, it has been found to be easier and more accurate to select the parameters empirically, for example by selecting three of the parameters to achieve substantial field cancellation and then adjusting the fourth parameter until the field at the components 18 has been reduced so that there is no significant heating of the metal components thereof. Thus, assuming the other three values are given,  $N_2$  might be determined as follows:

1. Wind the outer coil with the predetermined number of turns (19 in the example given).

2. Insert a magnetic field monitoring device such as a gauss meter in the central region of the coil.
3. Apply a dc current through the outer coil and monitor the magnetic field in the central region.
- 5 4. Locate one of the ends of the outer coil and using the wire extension from this coil, start winding the inner coil in the opposite direction of the outer coil.
5. As the inner coil is wound, monitor the strength of the magnetic field in the central region. Stop winding the inner coil when this field reaches zero.

Other empirical procedures might similarly be used for determining the parameter values in order to achieve substantial field cancellation at the center of the coil.

Figure 4C illustrates a magnetic flux pattern which might be achieved with the winding pattern of Figures 3A-3B. From Figure 4C, it can be seen that the magnetic field at components 18 can be reduced to substantially zero utilizing this technique. However, since this technique involves significant signal cancellation in the secondary coil, it results in a reduced energy transfer efficiency for the device. It may therefore not be suitable for use in applications where a high energy transfer efficiency is required.

Figure 3C illustrates an alternative to the embodiment shown in Figure 3B which to some extent reduces the loss of energy transfer efficiency resulting from the counter flowing current in coil 16B. For this embodiment, coil 16B' is a few turns of wire, for example one or two, having the diameter  $D_2$  but not electrically connected to the windings 16A'. The magnetic flux resulting from current flow in windings 16A' induce a current in winding 16B' which in turn produce a magnetic field countering that generated by that winding 16A. By suitable selection of both the number and diameter of the windings 16A' and 16B', field cancellation such as that shown in Figure 4C can be achieved.

In an alternative embodiment, the cage of the present invention is configured to increase the permeability in a flux pathway between the primary and secondary coils that is closest to the secondary coil. In one embodiment this is achieved by extending the high permeability shield material of cage 22 to a location within the flux pathway. This increases the total permeability of the flux pathway with a corresponding increase in coupling between the primary and secondary coils.

An exemplary implementation of this alternative embodiment of the cage is illustrated in Figure 5. As shown therein, cage 500 includes a base 502 and a lid 504. In this illustrative



embodiment, base 502 is cylindrical while lid 504 is shaped in the form of a disk. Base 502 includes an integral flange 506 that extends the cage material from base 502 into the magnetic flux pathway 508.

To increase the coupling between the primary and secondary coils, flange 506 is preferably in-line with the shortest flux pathway between the primary and secondary coils. In other words, flange 506 extends from base 502 immediately adjacent to secondary coil 512 to guide the magnetic flux lines back toward the primary coil. The extent to which the flange 506 extends away from base 502 is based on the mass and volume limitations of the device. However, flange 506 preferably does not have a thickness less than that which would cause saturation of the magnetic material, particularly at highest primary field strengths.

It should be understood that flange 506 may be the same or different high permeability material as base 502. In devices wherein flange 506 and cage 22 are of the same material, flange 506 and base 502 are preferably formed as a unitary device. However, in alternative embodiments, flange 506 may be attached to base 502 using well-known techniques.

Figure 6 is a simplified cross-sectional view of an alternative embodiment of a cage 600. Cage 600 includes a base 602 and an self-aligning or interlocking lid 604. In this illustrative embodiment, base 602 is cylindrical while lid 604 is shaped in the form of a disk. Base 602 includes vertical walls 606 onto which lid 604 is attached, typically by bonding.

Lid 604 includes an annular recessed shelf 608 circumferentially formed around mating surface 610 of lid 604. Shelf 608 is configured to receive vertical wall 606 of base 602 thereby preventing relative motion of lid 604 and base 602 during assembly. It should be understood that other features may be used to align and/or secure lid 604 with base 602, such as by threading, etc. Alternatively, mating surface 610 of lid 604 may have a track or groove configured to accept base vertical wall 606. It should also be noted that annular recessed shelf 608 may be configured as a square or any other shape to accept base 602.

Figure 7 is a cross-sectional view of an implantable device 702 housing a secondary coil 704. Cage 706 is positioned within secondary coil 704, as described above. Cage 706 serves to house electronic components 708 that generate heat, illustrated by arrows 710. In accordance with this embodiment of the present invention, heat in implanted device 702 is distributed to avoid localized high temperature regions as well as tissue necrosis.

Housing 702 is constructed of a relatively low thermal conductivity medium such as potting epoxy. Cage 706 preferably includes flange 712 similar to the flange described above

with reference to Figure 6. In accordance with this embodiment of the present invention, a heat distribution layer 714 is thermally coupled to cage 706 and housing 702. Heat generated by electronics 708 is transferred via conduction to cage 706. To facilitate the transfer of such heat into distribution layer 714 good thermal contact is maintained between distribution layer 714 and cage 706 using a thermally conductive medium. In addition, the largest contact area between distribution layer 714 and cage 706 suitable for the implemented design is implemented. For example, in the embodiment illustrated in Figure 7, flange 712 provides base 715 with the greatest area over surface 720 as compared to other surfaces of cage 706. Accordingly, distribution layer 714 is thermally coupled to cage 706 at surface 720. Similarly, distribution layer 714 is preferably thermally coupled to a substantial area of housing 702. This provides for the substantially uniform distribution of heat along housing 702. In the embodiment illustrated in Figure 7, distribution layer 714 is thermally coupled to the entire housing 702 other than the portion of housing 702 adjacent bottom surface 720 of cage 706.

In one embodiment, distribution layer 714 has a high thermal conductivity and a low magnetic permeability and low electrical conductivity. For example, in one preferred embodiment, distribution layer 714 is formed from alumina powder suspended in an epoxy medium. The thickness of the distribution layer 714 is preferably in the range of 2-10mm, although other thicknesses and materials may be used for a given application. In an alternative embodiment, distribution layer 714 is comprised of multiple alternating layers of high and low heat conductivity materials.

While specific embodiments have been disclosed above for reducing the magnetic field at the center of a TET device secondary coil so as to permit device electronics to be mounted in the coil without excessive heating, it is to be understood that other techniques for achieving this objective and/or other variations on the embodiments disclosed are within the contemplation of the invention. Thus, while the invention has been particularly shown and described above with reference to preferred embodiments, the foregoing and other changes in form and detail may be made therein by one skilled in the art while still remaining within the spirit and scope of the invention which is to be defined only by the following claims.

Further information is described in currently pending U.S. Patent Application 09/110,607 filed July 6, 1998 entitled "TET WITH MAGNETIC FIELD PROTECTED

COMPONENTS IN SECONDARY COIL,” and naming as inventors Fred Zarinetchi and Robert M. Hart, now currently pending, incorporated herein by reference in its entirety.

**CLAIMS**

1. A transcutaneous energy transfer device comprising:  
an external primary coil to which energy to be transferred is applied;  
an implanted secondary coil inductively coupled to said primary coil, each of said  
5 coils producing a magnetic field; and  
electronic components subcutaneously mounted within said secondary coil,  
characterized by the inclusion of a mechanism which reduces inductive heating of said  
components by said magnetic field.
- 10 2. The transcutaneous energy transfer device of claim 1, wherein said mechanism  
includes a cage formed of a high magnetic permeability material in which said electronic  
components are mounted.
3. The transcutaneous energy transfer device of claim 2, wherein said material is a  
15 ferromagnetic material.
4. The transcutaneous energy transfer device of claim 2, wherein the material of said  
cage is sufficiently thick so that magnetic field values in the material are well below  
saturation.
- 20 5. The transcutaneous energy transfer device of claim 2, wherein the material of said  
cage is sufficiently thick so that significant heat dissipation in the material does not occur.
6. The transcutaneous energy transfer device of claim 2, wherein the material of said  
25 cage is as thin as possible while still being sufficiently thick so that magnetic field values in  
the material are well below saturation and significant heat dissipation in the material does not  
occur.
7. The transcutaneous energy transfer device of claim 6, wherein said cage is thicker in  
30 areas of the cage experiencing high flux density and thinned in other areas.

8. The transcutaneous energy transfer device of claim 6, wherein said cage is formed of a layer of ferromagnetic material laminated with at least one layer of low magnetic conductivity material.

5 9. The transcutaneous energy transfer device of claim 1, wherein said mechanism includes said secondary coil being wound with a first number  $N_1$  of outer windings and a second number  $N_2$  of counter-wound inner windings,  $N_1$  being larger than  $N_2$ ,  $N_1$ ,  $N_2$  and the diameters of both the outer and inner windings being selected such that the magnetic field caused by the coils in the region of said components is reduced sufficiently to prevent  
10 significant component heating.

10 10. The transcutaneous energy transfer device of claim 9, wherein  $N_1$ ,  $N_2$  and the diameters of the windings are selected so that the magnetic fields caused by the windings substantially cancel in the region of said components.

15 11. The transcutaneous energy transfer device of claim 9, wherein  $N_1$  is approximately 19,  $N_2$  is approximately seven the diameter of the outer winding is approximately 2.5" and the diameter of the inner winding is approximately 1.5".

20 12. The transcutaneous energy transfer device of claim 1, wherein said mechanism includes said secondary coil being wound with a first number  $N_1$  of outer windings and including a second number  $N_2$  of inner windings in the magnetic field of the outer windings,  $N_1$  being larger than  $N_2$ ,  $N_1$ ,  $N_2$  and the diameters of both the outer and inner windings being selected such that the magnetic field caused by the coils in the region of said components is  
25 reduced sufficiently to prevent significant component heating.

13. A transcutaneous energy transfer device comprising:

an external primary coil;

an implantable secondary coil coupled to said primary coil;

30 a cage formed of a high magnetic permeability material located within said secondary coil to reduce inductive heating of electronic components mounted therein caused by a magnetic field of said primary and secondary coils,

wherein said cage has walls of varying thickness such that a lowest total mass is achieved without exceeding the saturation density of said cage material.

14. The transcutaneous energy transfer device of claim 13, wherein said thickness of said cage walls is a minimum thickness that results in magnetic flux density through said cage walls is approximately equal to said saturation density.

15. A transcutaneous energy transfer device comprising:  
an external primary coil;  
an implantable secondary coil coupled to said primary coil;  
a cage formed of a high magnetic permeability material located within said secondary coil to reduce inductive heating of electronic components mounted therein caused by a magnetic field of said primary and secondary coils,  
wherein said cage has a geometry configured to maximize permeability in flux pathway between the primary and secondary coils.

16. The transcutaneous energy transfer device of claim 15, wherein said cage has flanges that extend the high permeability shield material within the flux pathway.

17. The transcutaneous energy transfer device of claim 16, wherein said cage comprises:  
a cylindrical base;  
a lid shaped in the form of a disk; and  
said flanges integral with said base, said flanges extending a high magnetic permeable region from base into the magnetic flux pathway.

18. The transcutaneous energy transfer device of claim 17, wherein said flange is in-line with a shortest flux pathway between said primary and secondary coils.

19. The transcutaneous energy transfer device of claim 17, wherein said flange extends from base immediately adjacent to said secondary coil to guide said magnetic flux lines back toward said primary coil.

20. A transcutaneous energy transfer device comprising:

an external primary coil;

an implantable secondary coil coupled to said primary coil;

a cage formed of a high magnetic permeability material within said secondary coil to  
house electronic components, wherein said cage is comprised of:

a base; and

a self-aligning lid.

21. The transcutaneous energy transfer device of claim 20, wherein said base is  
cylindrical and wherein said lid is shaped in the form of a disk.

22. The transcutaneous energy transfer device of claim 20, wherein said base includes  
vertical walls and wherein said lid includes an annular recessed shelf circumferentially formed  
around a mating surface of said lid configured to receive said vertical wall of said base.

23. A transcutaneous energy transfer device comprising:

an external primary coil;

an implantable housing formed of a substantially low thermal conductivity medium;

a secondary coil, mounted within said implantable housing, coupled to said primary  
coil;

a cage formed of a high magnetic permeability material within said secondary coil to  
house electronic components; and

a heat distribution layer thermally coupled to said cage and to an internal surface of  
said housing.

24. The transcutaneous energy transfer device of claim 23, wherein said heat distribution  
layer is comprised of multiple alternating layers of high and low heat conductivity materials.

25. In a transcutaneous energy transfer system including a primary coil and an implantable  
secondary coil having an outer first winding having a first number of turns and a first diameter  
and an inner second winding having a second number of turns and a second diameter, a  
method for determining said second number of turns, comprising:

- a) winding said first winding with a predetermined number of turns;
- b) inserting a magnetic field monitoring device in a central region of said secondary coil;
- c) applying a dc current through said first winding while monitoring a magnetic field in the central region;
- 5 d) winding said second winding in a direction a direction of said first winding using a wire extension from said first winding;
- e) monitoring, as said second winding is wound in said step d), a strength of a magnetic field in the central region; and
- 10 f) stopping said winding of said second winding when the magnetic field strength reaches approximately zero.



1/4

FIG. 1

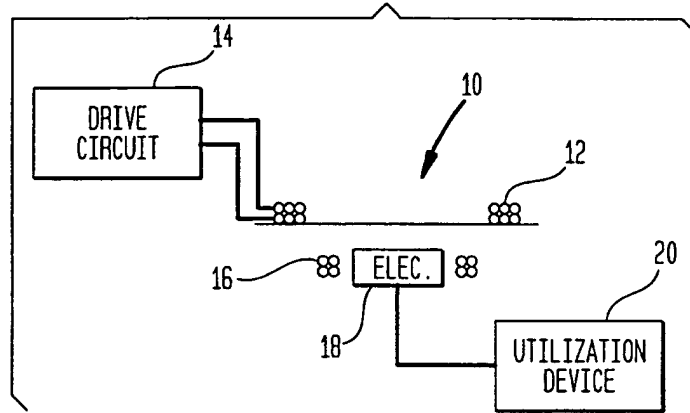


FIG. 2

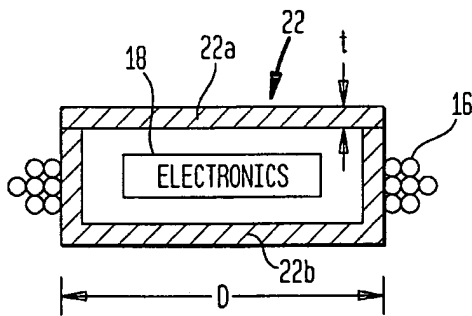


FIG. 3A

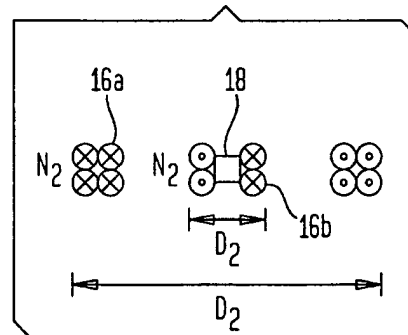


FIG. 3B

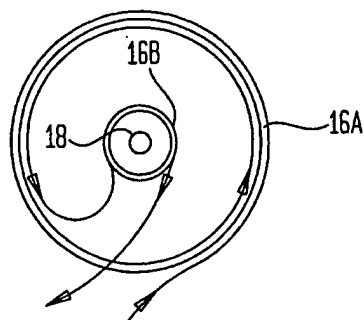


FIG. 3C

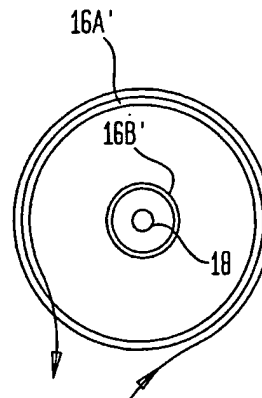


FIG. 4A

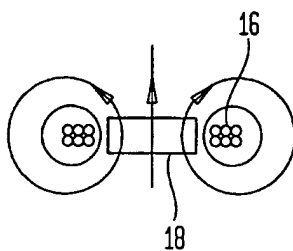


FIG. 4B

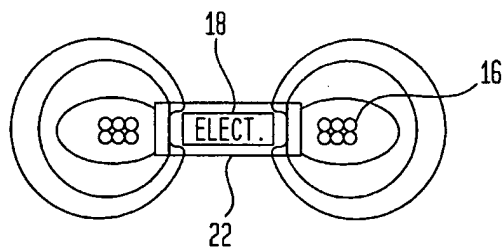


FIG. 4C

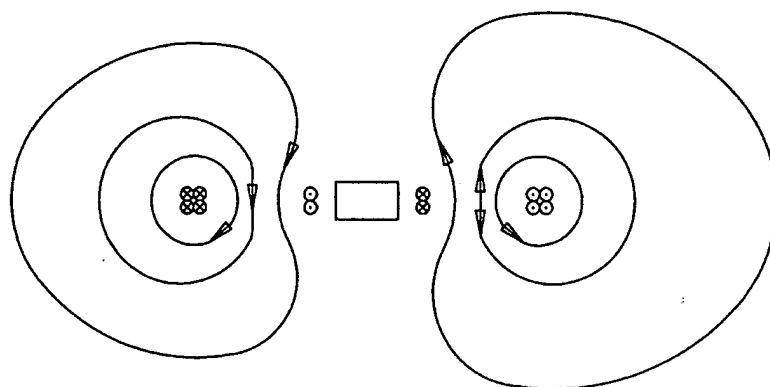


FIG. 5

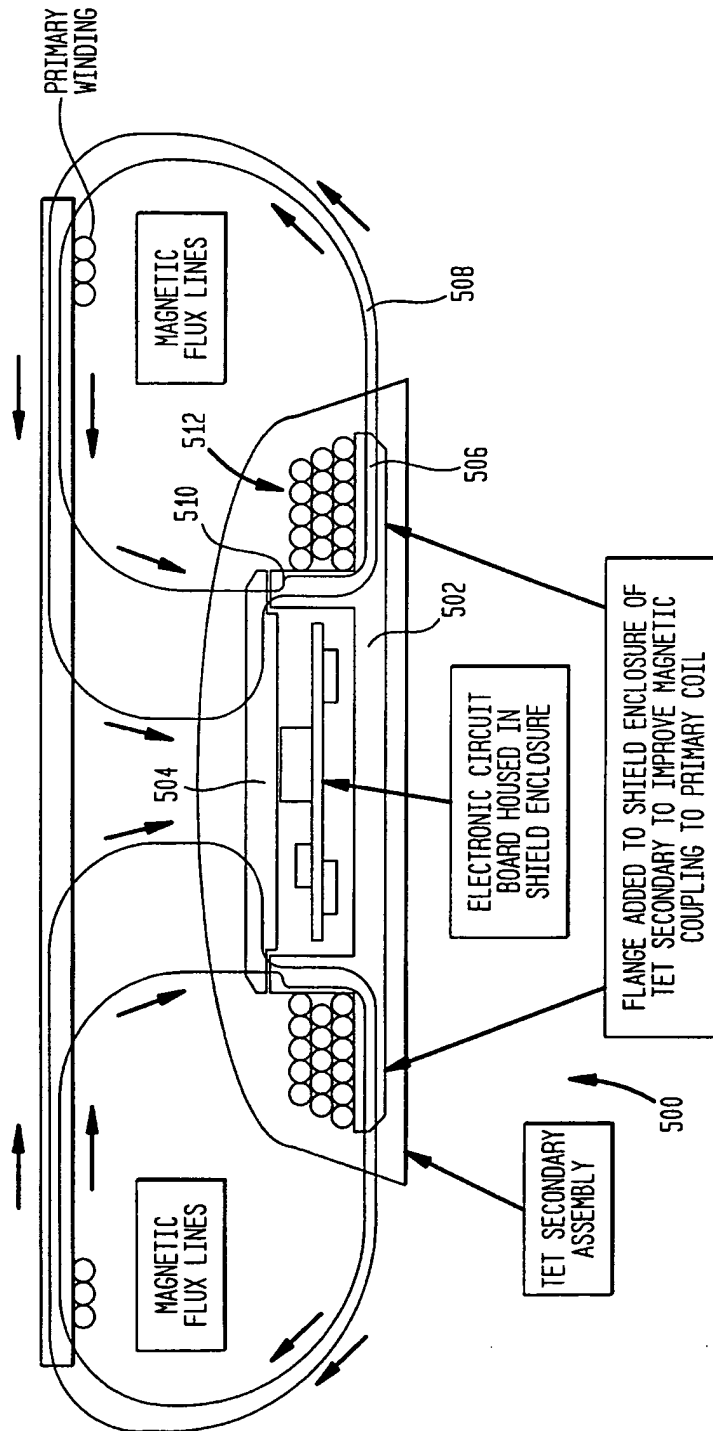


FIG. 6

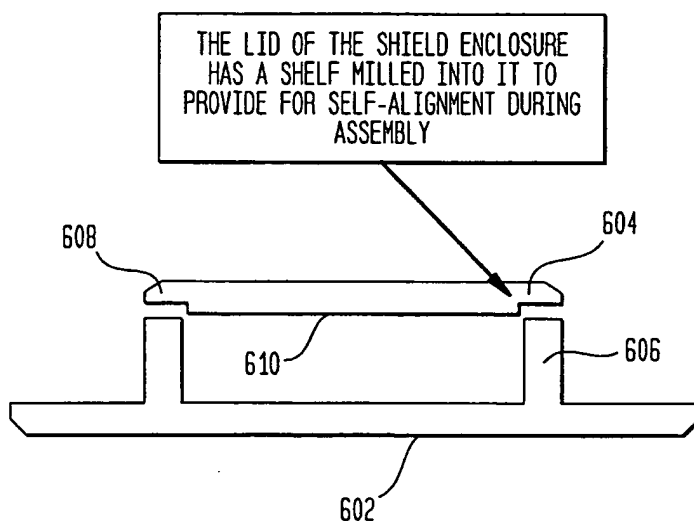


FIG. 7

